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STRATOSPHERIC MODULATION OF TERRESTRIAL CLIMATE DURING THE SOLAR CYCLE

Summary of Research

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1. Introduction

We summarize the primary accomplishments of the research efforts supported under NASA Grant NAG5-13492. The primary objective of our project is to provide an improved physical understanding of the mechanisms that are responsible for the existing empirical relationships observed between the solar cycle and tropospheric climate. Our focus is on the synoptic and dynamic linkages between the stratosphere and troposphere. Our scientific approach uses quantitative diagnostic analyses of data derived from atmospheric observations and ancillary model experiments. Substantial progress was made in these areas and an overview of our research efforts is provided below

2. Observational and model datasets

Our initial efforts included acquiring and formulating relevant monthly averaged data. Our diagnostic analyses not only required basic atmospheric field variables such as winds, geopotential heights, and air temperature but also nonlinear measures such as eddy heat and momentum fluxes (which require separating waves from the zonal-mean flow field in daily data prior to constructing monthly averages). We completed this task for 40+ years of both the NCEP/NCAR reanalyses and the ECMWF Reanalysis dataset (ERA-40). The ERA-40 data provide high quality observational atmospheric analyses (extending into the upper stratosphere) which are considered useful in characterizing long-term (decadal) variability, especially in the data sparse Southern Hemisphere. A combined consideration of separate results derived from the two datasets (which provide parallel observational records derived from independent data assimilation systems) permits tests of the statistical robustness of our observational and dynamical characterizations.

We also completed a series of general circulation modeling experiments at Georgia Tech using Version 3.0 of the Community Atmospheric Model (CAM). These experiments were designed to isolate the atmospheric dynamical structures forced by specified increases in total solar irradiance, incoming UV radiation and ozone concentrations (each mimicking solar cycle forcing). These related effects were studied separately and jointly in an idealized model setting focusing on the boreal winter circulation (when stratosphere-troposphere coupling is strong). In principle, these experiments provide a "clean" model framework for validating the physics of solar-induced stratosphere-troposphere coupling including an assessment of the linearity of the response to UV and ozone changes. Further details of these experiments can be found in Whitesides (2006).

3. Observational characterization of solar cycle response

We first characterized the atmospheric response to the solar cycle using a multivariate linear regression approach. This allows a separation of the atmospheric dynamical structures induced by the solar cycle from those independently forced by volcanoes, ENSO, the North Atlantic Oscillation, and the Quasi-Biennial Oscillation. We applied this approach to both the NCEP/NCAR and ERA-40 reanalysis datasets. We derived very similar atmospheric structures from the two datasets indicating that our observational characterization is robust. The primary result is the identification of a coherent north-south dipole in the extratropical zonal wind anomaly field extending from stratospheric altitudes downward into the middle and lower troposphere (Such circumpolar zonal wind anomaly structures are known as "annular modes"). A seasonal stratification indicates that the tropospheric signal is strongest during wintertime when stratosphere-troposphere dynamical coupling is most active. The atmospheric circulation anomaly features identified in our regression analyses were used as a basis for performing subsequent dynamical diagnoses of stratosphere-troposphere coupling in association of the solar cycle (discussed below). The above research results are presented in Black and Whitesides (2004, 2005) and Whitesides (2006).

4. Dynamical diagnoses of stratosphere-troposphere coupling

The main diagnostic tools used in our project include potential vorticity (PV) inversions, Eliassen-Palm (EP) fluxes (and their divergence), and the wave driving of the Transformed Eulerian mean circulation. The PV inversions are used to divide the atmospheric circulation anomaly field into separate parts related to stratospheric and tropospheric dynamical structures. EP fluxes (based upon eddy momentum and heat fluxes) provide a quantitative measure of Rossby wave propagation in the meridional plane. The net impact of anomalous Rossby wave activity on the zonal wind field (the so-called wave driving) is directly related to the EP flux divergence. These diagnostic tools were formulated and applied to atmospheric circulation structures identified in the simple linear regression analyses (discussed above).

Our diagnostic results indicate a relatively strong role for direct downward forcing of the tropospheric wind field by stratospheric dynamical structures. Although there is also evidence of a southward deflection of Rossby wave activity by the anomalous zonal mean flow (the indirect influence), this signature is primarily confined to stratospheric altitudes. Further, the pattern of tropospheric wave driving associated with the anomalous EP flux field is inconsistent with the observed tropospheric zonal wind pattern. Thus, it appears that the primary downward stratospheric influence that occurs during the solar cycle is likely a direct influence associated with variations in the meridional overturning (Hadley-type circulations). However, our results also indicate that the indirect influence plays a key role in facilitating the downward signal propagation within the stratosphere (Black and Whitesides 2005).

The grant has also supported basic research on the dynamical communication between the troposphere and stratosphere in association with so-called annular modes of variability (mentioned above). In particular, the Northern Hemisphere annular mode (NAM) accounts for a large fraction of the extratropical wintertime atmospheric variability. In McDaniel and Black (2005), we performed composite diagnostic analyses of daily variations in the NAM to identify the dominant processes responsible for the growth and decay of large amplitude NAM events. It was determined that low frequency planetary scale waves provide the primary dynamical forcing for short term intraseasonal variations of the NAM in both the stratosphere and troposphere. More specifically, we find strong evidence that this forcing is due to large-scale quasi-stationary anomalies over the North Atlantic region. Further, we have determined that NAM decay is linked to a collapse in the pattern of anomalous stationary wave forcing over the North Atlantic, which in turn helps promote the observed changes in the wave driving of the zonal mean flow. Although our study provides evidence for both direct and indirect downward stratospheric influences during NAM events, the former appears relatively weak in comparison to the latter.

We have also examined the impact of stratospheric final warming (SFW) events upon the extratropical large-scale circulation in the Northern Hemisphere (Black et al. 2006). SFW events were found to provide a strong organizing influence on the large-scale circulation of the stratosphere and troposphere during the period of spring onset. In contrast to the climatological trend, SFW events sharpen the annual weakening of the circumpolar westerlies *in both the stratosphere and troposphere* during spring onset. This evolution is associated with a robust large-scale dynamical coupling of the stratosphere and troposphere and results in a distinct regional circulation change in the lower troposphere. Importantly, the circulation change patterns identified are structurally distinct from the Northern Annular Mode (discussed above).

An in-depth dynamical analysis of boreal SFW events was performed in Black and McDaniel (2007b). As noted above, SFW events are linked to zonal wind deceleration signatures in the stratosphere and troposphere. The period of strongest stratospheric decelerations (SD) is marked by a concomitant reduction in the high latitude tropospheric westerlies. However, a subsequent period of tropospheric decelerations (TD) occurs while the stratospheric circulation relaxes back toward climatological conditions. Transformed Eulerian-Mean dynamical diagnoses reveal that the SD period is characterized by an anomalous upward Eliassen-Palm (E-P) signature at high latitudes extending from the surface to the middle stratosphere. The associated wave driving pattern consists of zonal decelerations extending from the upper troposphere to the mid-stratosphere. Piecewise potential vorticity tendency analyses further indicate that zonal wind decelerations in the lower and middle troposphere result, at least in part, from the direct response to latitudinal redistributions of potential vorticity occurring in the lower stratosphere. The TD period exhibits a distinct dynamical behavior with anomalous *downward* E-P fluxes in the high latitude stratosphere as the zero zonal wind line descends toward the tropopause. This simultaneously allows the stratospheric polar vortex to radiatively recover while providing upper tropospheric zonal decelerations (as tropospheric

Rossby wave activity is vertically trapped in the high latitude troposphere). Thus, during the TD period tropospheric decelerations are regarded as a subsequent indirect consequence of SFW events.

The nature of austral SFW events was examined in Black and McDaniel (2007a). Similar to boreal events, we found that austral SFW events provide a substantial organizing influence upon the large-scale atmospheric circulation in the Southern Hemisphere. In particular, the annual weakening of high latitude westerlies in the upper troposphere and stratosphere is accelerated during SFW onset. This behavior is associated with a coherent annular circulation change with zonal wind decelerations (accelerations) at high (low) latitudes. The high latitude stratospheric decelerations are induced by anomalous wave driving of upward propagating tropospheric waves. Longitudinally asymmetric circulation changes also occur in the lower troposphere during SFW onset with regionally localized height increases (decreases) at subpolar (middle) latitudes. Similar to boreal events, the tropospheric and stratospheric circulation change patterns identified are determined to be structurally distinct from the canonical Southern Annular Mode.

5. Diagnosis of model simulations

The CAM model simulations were analyzed in a similar fashion to the observationally-based results (Whitesides 2006). As theory predicts, in most of the model simulations we found that the stratospheric equator to pole temperature gradient increased while the polar night jet strengthened. An alteration in Rossby wave propagation associated with stratosphere-troposphere coupling was also observed. More specifically, the acceleration of zonal mean winds at mid- to high latitudes near the tropopause was accompanied by anomalous equatorward propagation of planetary waves within the troposphere, consistent with indirect stratosphere-troposphere coupling. The above signatures were most prominent in the experiments that explicitly incorporated ozone variations. Interestingly, however, the model experiments including all three affects did not produce the largest amplitude response. Furthermore, we determined that the separate responses are not additive (linear). Thus, our experiments demonstrate the complexity and nonlinearity of the extratropical dynamical response to the solar cycle.

6. Publications, meetings, education and public outreach

The grant provided primary support for the graduate research of Ms. Benton Whitesides, who successfully completed her M.S. thesis in June 2006 (Whitesides 2006). In addition, although public outreach was not a formal component of our project (as a supplementary EPO grant was not requested), I had the opportunity to formally mentor Mr. Thomas Christian (a high school student from Warner Robins, Georgia) on a high school science project directly related to the grant topic. Thomas won Grand Prize for his efforts in the Houston County Regional Science and Engineering Fair two years in a row, earning respective berths in the 2004 and 2005 International Science and Engineering Fair. Thomas' 2005 project entitled "The Connection Between Solar Variability and Annular Modes" received the US Air Force First Award of $3,000 at the 2005 International Science and Engineering Fair in Phoenix, Arizona. Finally, on the next page is a summary list of publications and presentations that received grant support.

Supported publications and presentations

Black, R.X., and B.W. Whitesides, 2004: Stratosphere-Troposphere Coupling and the Solar Cycle, *35th COSPAR Scientific Assembly*, Committee on Space Research.

(Abstract: www.cosis.net/abstracts/COSPAR04/02048/COSPAR04-A-02048.pdf)

Black, R.X., and B.W. Whitesides, 2005: Interannual Variability in the Troposphere- Stratosphere Climate System and the Solar Cycle, *16th Conference on Climate Variability and Change,* American Meteorological Society.

(Abstract: http://ams.confex.com/ams/Annual2005/techprogram/paper_85889.htm)

Black, R.X., and B.A. McDaniel, 2004: Diagnostic case studies of the Northern Annular Mode. *J. Climate,* **17,** 3990-4004.

(Manuscript: http://rxb.eas.gatech.edu/papers/black_mcdaniel_2004.pdf)

McDaniel, B.A., and R.X. Black, 2005: Intraseasonal dynamical evolution of the Northern Annular Mode. *J. Climate,* **18,** 3820-3839.
(Manuscript: http://rxb.eas.gatech.edu/papers/mcdaniel_black_2005.pdf)

Black, R.X., B.A. McDaniel, and W.A. Robinson, 2006: Stratosphere-Troposphere coupling during spring onset. *J. Climate,* **19,** 4891-4901.
(Manuscript: http://rxb.eas.gatech.edu/papers/black_mcdaniel_robinson.pdf)

Whitesides, B.W., 2006: Interannual zonal variability of the coupled stratosphere-troposphere climate system. M.S. thesis, Georgia Institute of Technology, Atlanta, GA.
(Thesis: http://etd.gatech.edu/theses/available/etd-07072006-090134/)

Black, R.X., and B.A. McDaniel, 2007a: Interannual variability in the Southern Hemisphere circulation organized by stratospheric final warming events. *J. Atmos. Sci.*, **64,** 2968-2974.
(Manuscript: http://rxb.eas.gatech.edu/papers/black_mcdaniel_2006a.pdf)

Black, R.X., and B.A. McDaniel, 2007b: The annular dynamics of Northern Hemisphere stratospheric warming events. *J. Atmos. Sci.,* **64,** 2932-2946.
(Manuscript: http://rxb.eas.gatech.edu/papers/black_mcdaniel_2006b.pdf)